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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01F 3/06

A1

(11) International Publication Number: WO 99/28919

(43) International Publication Date: 10 June 1999 (10.06.99)

(21) International Application Number: PCT/EP98/07743

(22) International Filing Date: 30 November 1998 (30.11.98)

(30) Priority Data:
9725338.9 28 November 1997 (28.11.97) GB

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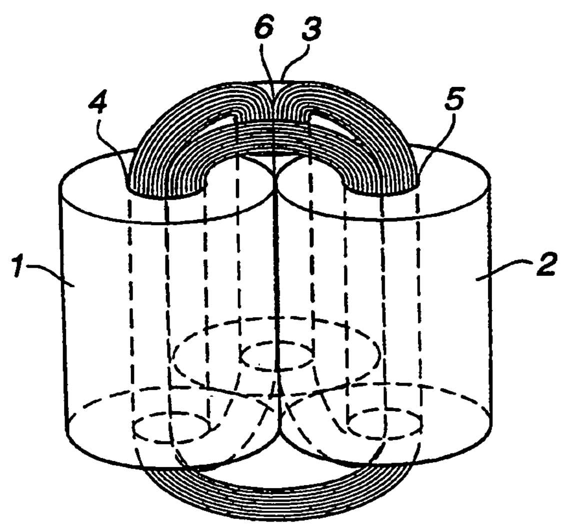
(81) Designated States: AL, AM, AT, AT (Utility model), AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, CZ (Utility model), DE, DE (Utility model), DK, DK (Utility model), EE, EE (Utility model), ES, FI, FI (Utility model), GB, GD, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SK (Utility model), SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: MAGNETIC CORE ASSEMBLIES

(57) Abstract

A high voltage stationary electromagnetic device comprising a core (7-9) of magnetic material having a relative permeability greater than 1 and current-carrying winding means (1-3) for generating an H-field. The core (1-3) is constructed and arranged so that, in use of the core assembly, current carried by the winding means gives rise to a B-field in the core which substantially follows the H-field.



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Magnetic Core Assemblies

Technical Field

This invention relates to a high voltage stationary electromagnetic device of the kind comprising a magnetic core of magnetic material having a relative permeability greater than 1 and current-carrying winding means for generating an H-field. In particular, but not exclusively, the invention relates to such high voltage stationary machines as power transformers with an output range from some 100 kVA up to more than 1000 MVA and voltages from 3 to 4 kV, particularly from 10 kV, up to very high transmission voltages, e.g. 400 kV to 800 kV. The invention is also applicable to other non-rotating electrical machines or devices, such as reactors (sometimes referred to hereinafter as inductors). The invention also relates to a magnetic core assembly.

Background of the Invention

Magnetic cores are constructed from ferromagnetic materials which should ideally have low reluctance for the magnetic flux, high saturation, low coercivity and low remagnetising losses. All current commercially used magnetic core materials are based on iron and its alloys with most power transformers having magnetic cores made of laminated iron sheet. Pure iron has a magnetic flux density saturation level of about 2.2 T and can be treated for a low coercivity force and low remagnetising losses. The remagnetising losses can be affected by grain orientation, impurities and internal stresses.

Varying magnetic flux induces eddy currents within the core material itself. The losses from these eddy currents in laminated cores are directly proportional to the conductivity of the core material, the square of the material thickness, the flux density and frequency of operation. Burrs on the laminated core sheets produced as

a result of the manufacturing process also increase the losses. For low eddy current losses, the sheet thickness should be as small as possible. However, a problem is that for a given insulation layer the space factor decreases for thinner sheets. The trend in core design has been towards creating thinner laminated core sheets and, with better manufacturing techniques creating flatter and smoother surfaces with thinner insulation coatings, even thinner sheets can be used. The thickness of transformer core steel sheet is today typically 0.3 mm.

A major breakthrough in core steel manufacture was the introduction of grain orientation. Core steel consists of grains with a cubic lattice structure, the preferred magnetic orientation being along the fourfold axes of the lattice. With a flux orientation along the sheet it is also of benefit to have the grains oriented along the sheet. The process that produces such an effect is called "grain orientation".

Laminated steel sheets may have an inner thin glass film coating applied during a cooling process. In addition to the inner glass film coating, the core sheets may have an outer phosphate coating as a protective and insulating layer.

Much interest has been paid to sheets of amorphous alloys as possible core materials. The random arrangement of the atoms results in remagnetisation losses in the core disappearing and in very high resistivity of the core which reduces eddy current losses. The main disadvantage with amorphous alloys is that the magnetic flux density with saturation only goes up to about 1.4 to 1.6 T.

Recently suggestions have been proposed for using soft magnetic composites, for example soft magnetic electrically insulated powder, as magnetic material for core sections in rotating electrical machines, transformers and inductors. The magnetic flux density at saturation lies

midway between that of oriented material and amorphous material, i.e. about 1.6 to 1.8 T. Such soft magnetic composite material and certain of its applications are described in a brochure from Höganäs, SMC Update, Vol. 1, April 1997, and in a report "Powdered soft magnetic materials for medium frequency applications" presented at a conference on "Soft Magnetic Materials" in San Francisco, February 1996. The applications discussed are mainly concerned with very small power ratings at a frequency of around several kHz.

There are specific advantages and disadvantages in making magnetic cores for magnetic transformers from the three different core materials referred to above.

The advantages of transformer cores made from oriented sheet are that they have relatively low hysteresis losses and relatively high magnetic saturation. However, the material is relatively expensive and material wastage during punching can be extensive.

The advantages of transformer cores made from amorphous sheet are that they have insignificant hysteresis losses and the eddy current losses are small. However, the material has a low magnetic saturation and is expensive.

An advantage of transformer cores made from soft magnetic composites is that the cores can be shaped, without wastage of material. However, such composites still have a limited magnetic saturation, have high hysteresis losses and entail high no-load currents.

The above analysis has concentrated mainly on the alternative materials used in magnetic cores of power transformers. Normally conventional power transformers still use magnetic cores of laminated sheet material made of these materials. The following part of the description relates to the design and construction of magnetic cores and windings of known power transformers.

Transformers can be classified as being either core type or shell type. In a core type transformer, the coils appear to surround the core whereas in a shell type transformer the core appears to surround the windings. A core type transformer is shown in Figure 1 and comprises a number of core limbs connected by upper and lower yokes which together form one or more core windows. The core limbs are typically cylindrical in shape around which the coils are arranged. For normal power type transformers, the coils are also cylindrical and are arranged concentrically. The coils are normally preformed and are slid down over the pre-made core limbs after which the yokes are connected to the core limbs. The coils with insulation, support parts, cooling channels and the like fill the core window(s).

In a shell type transformer according to Figure 2, each coil has a rectangular cross-section. Groups of coils are stacked together to form winding packets and the core is built up around these packets.

A core configuration for a conventional three-phase power transformer is shown in Figure 3. The windings for each of the phases are located on their own limbs which means that there are three limbs which are magnetically coupled together by upper and lower yokes. The sum of the magnetic fluxes in the three limbs is equal to zero when the magnetic flux in each leg is defined according to the directions shown in Figure 3. In the yokes, the limb flux divides and has its return path via the other two limbs. This means that a certain amount of magnetic flux from one of the outer limbs has to traverse to the opposite outer limb for certain parts of the cycle. Furthermore, the cross-sectional area of the yokes has to be at least the same as the cross-sectional area of the limbs.

Low magnetisation current, efficient utilisation of core steel and low loss properties have been reflected in the shape of core sheets and the stacking procedure in today's power transformers. A more detailed illustration of

the present design of magnetic core for a power transformer is shown in Figures 4 and 5. The connection between limb and yoke is often arranged at a 45° mitred joint. As shown in Figure 4, the laminated sheets are layed in packets of two or four sheets with the joints displaced relative to adjacent packets. Such an overlapping joint arrangement provides the core with a rigid mechanical structure and reduces the fringe effect for the flux traversing the joints.

In recent years, an alternative joint pattern, known as the "lap step", shown in Figure 5, has attained a certain acceptance. By making a step-wise shift of the joints, it is possible to reduce the magnetisation losses between the limb and yoke still further.

Transformers have been used in the electrical distribution industry for more than a hundred years. One of the first patents in that area, German patent DE-40414, dated 1887, describes transformer and core constructions which, even if formed as a ring cored transformer, are more or less direct predecessors of today's core transformers and shell transformers. Figure 6 shows a core transformer comprising a laminated iron core about which is wound a toroidal coil or coils of copper wire. Figure 7 shows a shell transformer comprising coil or coils wound around the core which comprises a coil wound toroidally with iron wire.

Following the introduction of the three-phase system, there have been a very large number of different designs of transformers and their associated core constructions. The presently dominant design of core transformer is still the generally known construction shown in Figure 4.

An example of known transformer core technology is described in GB-A-854,728 and shown in Figures 8 and 9. The core construction described comprises three core limbs each carrying coils made from laminated sheets. The opposite ends of each core are bent through 90° (see Figure 9) in

order to form parts of the yokes of the transformers. The three core limbs are then placed so that they form a three-armed star as shown in Figure 8 with the arms equally angularly spaced apart. The sheets of the yoke are stacked together in the middle of the star. A variant of this design is shown in Figure 10 and is described in GB-685,416. Figure 11 shows another transformer design disclosed in GB-A-965,741 which has many similarities magnetically with today's designs discussed below.

Another core construction is described in GB-A-805,721 and is shown in Figure 12. This core construction consists of a triangular prismatic arrangement. Each core limb is formed by the intersection of two core packet limbs which meet at a V-shaped angle. One disadvantage of this known construction is that the joints between core packet limbs and the yokes do not lie in a plane as they do in the construction shown in Figures 4 and 5.

In a transformer winding, it can broadly be said that from the point of view of an applied or induced voltage, a quasi-stationary voltage across the winding is distributed equally onto each turn of the winding, i.e. the turn voltage is equal for all the turns and the voltage increases linearly with the turns. From the point of view of impulse voltage and corresponding electric potentials, however, the situation is completely different. One end of a winding is usually connected to earth. This means that the electric potential of each turn increases non-linearly from practically zero in the turn which is nearest earth potential up to a potential in the turns which are at the other end of the winding and which correspond to a considerable part of the implied impulse voltage. This potential distribution determines the composition of the insulation system for the winding since it is necessary to have sufficient insulation both between adjacent turns of the winding and between each turn and earth potential.

The turns in an individual coil are normally brought together into a geometrically coherent unit, physically delimited from the other coils. The distance between any two coils is also determined by the dielectric stress which may be allowed to occur between the coils. This means that a certain given insulation distance is also required between the coils. Sufficient insulation distances are also required to other electrically conducting parts within the electric field from the electric potential occurring locally in the coils.

The general aim in the design of prior art transformers has been to have as large a quantity of conductor material as possible within the given area limited by the size of the transformer window. In addition to the conductor material, the transformer window must also accommodate cooling channels and the insulating material associated with the coils. In this way, windings with insulation and winding support parts represent large volumes which are subjected to high electrical field strengths arising in and around the active electro-magnetic parts of the transformer.

With the general aim of having as much conductor material within each transformer window, and with the additional aim of keeping transformer production costs and transportation costs as low as possible, the accepted core design today is as shown in Figures 4 and 5 with rectangularly shaped windows having inner and outer 90° corners defined by the stacked laminations. The limbs of such a transformer core are, as a rule, designed to have an approximately circular cross-section which results in the magnetic flux in the limbs, apart from the corner regions where the limbs connect to the yoke, being relatively evenly distributed over their whole cross-section.

From the point view of magnetic flux, a core construction according to Figures 4 and 5 is disadvantageous. With the 90° inner corners of the windows,

i.e. where the limbs connect to the yokes, the core material experiences a very high flux concentration or density of lines of force. Correspondingly, the 90° outer corners of the windows experience a very low flux density. This results in a high asymmetry in the magnetic flux in the transition between limbs and yokes. Such an asymmetric flux:

- leads to flux distortion which causes overtones producing additional losses;
- causes an undesirable temperature distribution in the core with elevated temperatures at the corners of the core;
- causes asymmetrical mechanical stresses in the core, especially at its corners;
- causes vibration and thus noise;
- causes unbalanced short circuit forces; and
- causes a flux concentration in the inner corners of the windows which can give rise to magnetic saturation of the material.

It is difficult to understand the loss mechanism present at the corners of transformer windows. Instead of trying to eliminate the corners, prior art designs have proposed, for example, intentionally increasing the distance between parts of the joints or increasing the overlap of the laminated sheet at the corners.

Another disadvantage of prior art transformers is that, when operated, they give rise to a not-insignificant magnetic scatter field which can be a health risk to people in the immediate vicinity of the transformer.

Since the following account of the invention is based primarily on electromagnetic field theory, in particular magnetic field strength, magnetic flux density and electric field strength, these concepts are described below.

Magnetic field strength H (usually referred to as the "H-field") is measured in A/m and arises around a current-

conducting conductor. The H-field is proportional to the magnitude of the current and decreases with distance from the conductor.

Magnetic flux density B (usually called the "B-field") is measured in T and arises as a consequence of the magnetic field strength. In vacuum or air, magnetic flux density is proportional to the magnetic field strength multiplied by a factor μ_0 (the permeability of free space). In a ferromagnetic medium, the magnetic flux density increases corresponding to the relative permeability μ.

Electric field strength E (usually referred to as the "E-field") is measured in V/m and arises around a conductor which has an electric tension or voltage relative to another potential, for example earth potential. The electric field strength is proportional to the magnitude of the electric tension and decreases with distance from the conductor.

Summary of the Invention

An aim of the present invention is to provide a high voltage stationary electromagnetic device, such as a transformer or inductor, with an improved design of magnetic core.

According to one aspect of the present invention there is provided a high voltage stationary electromagnetic device as claimed in the ensuing claim 1.

The H-field which surrounds current carrying air-cored windings of specific construction and relative arrangement can be calculated quite closely for every point around the winding(s) for both direction and magnitude. The present invention provides a core of magnetic material arranged in association with the winding(s) to produce a B-field which follows the path of the H-field of the corresponding arrangement of air-cored winding(s). Thus the magnetic core can be designed so that there is practically

homogeneous flux in all parts of the core, e.g. in both core limbs and yokes, and in the transition between such different core parts. This means that the difference between maximum and minimum magnetic flux density in different parts of the core is small which in turn means that the magnetic materials of the core can be exploited in a much better way than has been possible previously since the majority of the disadvantages discussed above of known core designs can be eliminated. In order to achieve this with transformer cores, the core is conveniently designed so that no sharp or right-angled corners are allowed to exist in the magnetic flux carrying circuit which will give rise to compression of lines of force so producing the problems referred to above. This approach contrasts with known transformer magnetic core designs having windows with sharp corners resulting in an inhomogeneous B-field distribution around the core with the disadvantages that accrue. These concentrations in the B-field occur when there are abrupt changes of orientation in the magnetic material at corners of the core.

If the stationary electromagnetic device according to the invention comprises a power transformer, it has:

- a B-field as high and evenly distributed as possible for a given magnetisable material.
- lower iron losses.
- a lower sound level.
- a lower material wastage during core construction.
- a total weight which is reduced compared with a conventional transformer.
- a geometry which can be adapted to the actual application. Thus, by way of example, the design of a rail mounted locomotive transformer will be considerably different from a transmission/ distribution transformer.
- a considerable reduction in the scattered magnetic field around and from the transformer compared with a conventionally designed transformer.

In practice, the shaping of the core to the ideal no-load, air-cored H-field of the windings arrangement, is achieved by incorporating curved core portions and eliminating sharp bends in the core design.

Conveniently the magnetic core can be designed as a wire wound core which enables the core to be made as near as possible to the optimal design in which there are parallel H- and B-fields. A core wound from wire or cable, preferably of oriented material, can be shaped so that the magnetic lines of force in the core, that is the B-field, become parallel with the H-field produced under no-load by at least one current carrying air-cored primary coil.

A wire wound core requires some form of magnetic flux transfer between the wires. For instance, the magnetic characteristics of a magnetic core can be improved if the bundle of wires from which the core is produced is baked or cast in an easily shaped magnetic material, for example soft magnetic powder material or a compactable magnetic material, such as a magnetic paste or slurry, comprising a viscous dispersion in a fluid of a magnetic powder coated with an insulating layer. The baking or casting results in the wire wound core having mechanical stability. It also produces a near perfect flux transfer between the wires. An alternative magnetic core design comprises a polymer matrix having a relative permeability greater than one. The polymer matrix can, for example, be an intrinsically magnetic polymer or a non-magnetic polymer with a magnetic filler.

The wire wound core, suitably comprising a bundle of wires, may be made from wires having a hexagonal, rectangular or circular cross-section.

Preferably each winding is wound from cable having inner electrically conducting means and surrounding outer solid electrically insulating means preferably comprising magnetically permeable plastics material within which the

electric field is confined in use of the magnetic core assembly. Preferably the electrically insulating means comprises an inner layer of semiconducting material in electrical contact with said electrically conducting means, an outer layer of semiconducting material at a controlled electrical potential along its length and an intermediate layer of electrically insulating material between the said inner and outer layers.

In this specification the term "semiconducting material" means a material which has a considerably lower conductivity than an electric conductor but which does not have such a low conductivity that it is an electrical insulator. Suitably, but not exclusively, the semi-conducting material should have volume resistivity of from 1 to 10^5 ohm·cm, preferably from 10 to 500 ohm·cm and most preferably from 10 to 100 ohm·cm, typically about 20 ohm·cm.

The electrically insulating means is suitably of unitary form with the layers either in close mechanical contact or, more preferably, joined together, e.g. bonded by extrusion. The layers are preferably formed of plastics material having resilient or elastic properties at least at ambient operating temperatures. This allows the cable forming the winding to be flexed and shaped into the desired form of the winding. By using for the layers only materials which can be manufactured with few, if any, defects having similar thermal properties, thermal and electric loads within the insulation are reduced. In particular the insulating intermediate layer and the semiconducting inner and outer layers should have at least substantially the same coefficients of thermal expansion (α) so that defects caused by different thermal expansions when the layers are subjected to heating or cooling will not arise. Ideally the layers will be extruded together around the conducting means.

Conveniently the electrically insulating intermediate layer comprises solid thermoplastics material, such as low

density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethylpentene (PMP), ethylene (ethyl) acrylate copolymer, cross-linked materials, such as cross-linked polyethylene (XLPE), or rubber insulation, such as ethylene propylene rubber (EPR), ethylene-propylene-diene monomer (EPDM) or silicone rubber. The semiconducting inner and outer layers may comprise similar material to the intermediate layer but with conducting particles, such as particles of carbon black or metal, embedded therein. Generally it has been found that a particular insulating material, such as EPR, has similar mechanical properties when containing no, or some, carbon particles.

The screens of semiconducting inner and outer layers form substantially equipotential surfaces on the inside and outside of the insulating intermediate layer so that the electric field is confined between the inner and outer layers in the intermediate layer. In the case of concentric semiconducting and insulating layers, the electric field is substantially radial and confined within the intermediate layer. In particular, the semiconducting inner layer is arranged to be in electrical contact with, and to be at the same potential as, the conducting means which it surrounds. The semiconducting outer layer is designed to act as a screen to prevent losses caused by induced voltages. Induced voltages in the outer layer could be reduced by increasing the resistance of the outer layer. The resistance can be increased by reducing the thickness of the outer layer but the thickness cannot be reduced below a certain minimum thickness. The resistance can also be increased by selecting a material for the layer having a higher resistivity. On the other hand, if the resistivity of the semiconducting outer layer is too great, the voltage potential midway between adjacent spaced apart points at a controlled, e.g. earth, potential will become sufficiently high as to risk the occurrence of corona discharge in the insulation with consequent erosion of the insulating and semiconducting layers. The semiconducting outer layer is

therefore a compromise between a conductor having low resistance and high induced voltage losses but which is easily connected to a controlled potential, typically earth or ground potential, and an insulator which has high resistance with low induced voltage losses but which needs to be connected to the controlled potential along its length. Thus the resistivity ρ_s of the semiconducting outer layer should be within the range $\rho_{min}<\rho_s<\rho_{max}$, where ρ_{min} is determined by permissible power loss caused by eddy current losses and resistive losses caused by voltages induced by magnetic flux and ρ_{max} is determined by the requirement for no corona or glow discharge. The resistance per axial unit of length of the semiconducting layer is typically from 5 to 50,000 $ohm.m^{-1}$, preferably from 500 to 25,000 $ohm.m^{-1}$, and most preferably from 2,500 to 5,000 $ohm.m^{-1}$.

By connecting the semiconducting outer layer to earth potential, or to some other controlled potential, at spaced apart intervals along its length, the need for an outer metal shield and protective sheath to surround the semiconducting outer layer is eliminated. The diameter of the cable is thus reduced allowing more turns to be provided for a given size of core winding.

According to another aspect of the present invention there is provided a magnetic core assembly for a stationary electromagnetic device, comprising a core of magnetic material having a relative permeability greater than 1 and current-carrying winding means for generating an H-field, characterised in that the core is constructed and arranged so that, in use of the core assembly, current carried by the winding means gives rise to a B-field in the core which substantially follows the said H-field.

<u>Brief Description of the Drawings</u>

Embodiments of the invention will now be described, by way of example only, with particular reference to the accompanying drawings, in which:

Figures 1 to 12 show schematically different embodiments of prior art magnetic core assemblies and transformers;

Figures 13 to 16 are schematic views of windings and core assemblies which illustrate the principle of the present invention;

Figures 17a to 20a and 21 to 24 are schematic perspective view of different embodiments of magnetic core assemblies of high voltage stationary electromagnetic devices according to the invention;

Figures 17b to 20b are plans of the magnetic core assemblies shown in Figures 17a to 20a, respectively;

Figures 25 to 29 are schematic perspective views of corner pieces for use in modifying conventional magnetic core assemblies; and

Figure 30 is a schematic perspective view of a modified limb/yoke of a magnetic core.

Description of Embodiments

Figures 13 to 16 illustrate the general principles of the present invention. In particular, Figure 13 shows the H-field that surrounds an air-cored circular cylindrical current-carrying winding. If two air-cored current-carrying windings a and b are placed close to each other a resulting H-field is obtained according to Figure 14. The H-field has field lines extending in a curved path between similar ends of the two windings. The introduction of magnetic material in the form of a magnetic circuit which passes through both of these windings will modify this H-field. The present invention, however, is based on the provision of a magnetic core having portions which follow as closely as possible the H-field present when the windings are not arranged around magnetic core material, i.e. as shown in Figure 14.

Figure 15 shows how a magnetic core can be designed as a closed loop which passes through the coils or windings a and b. In this respect, the magnetic core can be considered to comprise two straight limbs connected at the top and bottom by curved yokes. The yokes are designed to follow the portions of the H-field distribution which would be present if the windings were air-cored, i.e. assuming the magnetic material is not present. The B-field in the magnetic core is essentially parallel with the H-field produced when the magnetic material is not present. The upper and lower yokes are of generally curved or arcuate shape and have a substantially constant cross-sectional area. It is considered that the magnetic material of the core is placed in such a way that the centre line of the yokes will follow the centre line of the H-field produced by the coreless windings or the H-field from the windings in a transformer at no load.

Figure 16 shows a modified core assembly in which the magnetic core is generally toroidal in form and the windings have a curved form. Such a shape of core provides, to a large degree, a homogeneous flux distribution through the entire core. The design, moreover, provides an optimal use of magnetic material.

It will be appreciated that in practice it is difficult to fulfil the optimum design requirements, i.e. for the core to be shaped to conduct the magnetic flux so that, in every part of the magnetic circuit, the B-field is parallel with the known H-fields produced by the current carrying coils or windings. The embodiments described below constitute some of the possible alternative solutions which aim to fulfil the optimal design concept.

In the core assemblies described below, each winding is formed from inner electrically conducting means and surrounding outer solid electrically insulating means, preferably comprising magnetically permeable plastics material within which the electric field is confined in use

of the magnetic core assembly. The electrically insulating means conveniently comprises an inner layer of semiconducting material in electrical contact with the electrically conducting means, an outer layer of semiconducting material at a controlled electrical potential, e.g. earth potential, along its length and an intermediate layer of electrically insulating material between the inner and outer layers. These layers of the electrically insulating means are conveniently applied by extrusion. Typical examples of the insulating material are ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) and the semiconducting layers may be of a similar material incorporating particles of electrically conductive material, e.g. carbon particles or metallic particles. In use the E-field is contained radially between the inner and outer layers of semiconducting material.

Figures 17a and 17b, 18a and 18b, 19a and 19b, 20a and 20b, 21, 22, 23 and 24 represent preferred embodiments of magnetic core assemblies of a high voltage stationary electromagnetic device according to the invention in the form of a power transformer. In the following description, the same reference numerals have been used to identify the same or similar parts in the various different embodiments. All the magnetic core assemblies have winding portions, which are preferably generally straight, around which windings are arranged and at least two curved portions.

The transformer shown in Figures 17a and 17b comprises three winding packets 1, 2 and 3, each of which comprises a concentric arrangement of a primary and a secondary winding. The winding packets have concentric tubular cylindrical inner openings 4, 5 and 6 for receiving parts of a wire wound core. The winding packets are positioned against each other so that their cylindrical outer envelope surfaces are tangential to each other. This means that the direct lines of connection between the centres of the end surfaces at each end of the winding packets form an equilateral triangle. The magnetic core of

the transformer comprises three identically similar core sections 7, 8 and 9 comprising a bundle of oriented wires or cable. Each core section consists of two straight core limbs and connecting curved upper and lower yokes. The cross sectional area of each of the core sections is approximately half the cross sectional area of the tubular cylindrical opening of each winding packet. Core section limbs from two different core sections are situated in each of the tubular cylindrical openings. The design of transformer is similar in many respects to that shown in Figure 12 except that in the present design the transformer does not have large insulation distances between winding packets and the core has no right-angled or sharp corners.

Figures 18a and 18b show a three-phase core transformer similar to the embodiment shown in Figures 17a and 17b but provided with modified core sections 10, 11 and 12. The yokes of each core section, in addition to being curved in a plane containing the limbs of the core section, are also bent out of this plane towards each other. At each end of the core assembly there is thus a small opening 13 between the yokes of the core sections 10 to 12. This design of core assembly takes account of the influence on the H-field on any one winding packet by the two other winding packets.

Figures 19a and 19b show an embodiment of a three-phase shell transformer having three winding packets 1, 2 and 3 and three identical core sections 14, 15 and 16. Each cylindrical inner opening 4-6 contains two straight core section limbs from different core sections 14 to 16. Curved core section yokes are bent and shaped so that they form a three armed star-shaped yoke 17 with a common middle core limb as seen in Figures 19b. This embodiment is similar to the transformer shown in Figure 8 except that in the present design of transformer there is no need for the large insulation distances between the winding packets and the magnetic core has no right-angled corners.

Figures 20a and 20b shown a variant of the three-phase transformer shown in Figures 17a and 17b where the winding packets 18, 19 and 20 are curved or shaped so as to be in the form of a section of a toroidal ring. Both ends of each pair of adjacent winding packets form tangents to each other in the same way as the end surfaces of the transformer shown in Figures 17a and 17b. Core sections 7, 8 and 9 are similar in the two embodiments. It is of course possible for the shaped winding packets shown in Figures 20a and 20b to be provided with core sections similar to those shown in Figures 18a and 18b and, respectively, 19a and 19b. The upper and lower connecting yoke portions have a different curvature to the limb portions about which the windings are formed.

Figures 21 to 24 show embodiments similar to those shown in Figures 17a and 17b, 18a and 18b, 19a and 19b and 20a and 20b, respectively. The differences in the embodiments shown is that in Figures 21 to 24 the wire wound cores have been replaced by core sections made of soft magnetic powder composites.

The various embodiments shown in Figures 17 to 24 show with great clarity how core assemblies can be designed and optimised so that the core sections are designed so as not to have any sharp corners or bends and to be curved so as to follow the H-field that would be present at no load around the winding packets if no magnetic material were present, i.e. the winding packets were air-cored. Thus the B-field produced in use in the core sections substantially follows the H-field.

The invention also finds application in high voltage stationary electromagnetic devices having magnetic cores made of laminated sheet material. Such cores often have windows with right-angled corners and the present invention covers the modification of such cores by providing flux-carrying corner pieces in the right-angled corners of the core. As previously mentioned, the provision of rounded

transitions in conventional laminated core designs is difficult from a practical point of view using conventional punching and assembly techniques. There is also wastage of core material if rounding of the corners or core windows is attempted.

Figures 25 to 29 show various corner sections which can be made of compactable magnetic material, e.g. soft magnetic powder or a compactable magnetic slurry of a magnetic material.

In Figures 25 to 29, the embodiment shown in Figure 25 are intended to fit in the corners marked with circles of the windows shown in the core assembly of Figure 2. The corner pieces shown in Figure 26 are intended to fit in the circled corners of the core shown in Figure 3. The corner pieces shown in Figure 27 provide rounded corners for the section of the core marked with a circle in Figure 4. the corner piece shown in Figure 28 provides a rounded corner for the core section marked with a circle in Figure 8. The corner member shown in Figure 29 provides a rounded corner for the section identified by a circle in Figure 29.

The joint between a centre limb and yoke, i.e. the area inside the section marked with a square in Figure 3, can be provided by a construction as shown in Figure 30. Thus Figure 30 shows a T-shaped joining piece for joining a limb and yoke pieces together.

The invention has been described in particular with reference to transformers and in particular power transformers having cores with more than one winding. However, the invention also has application to other high voltage stationary electromagnetic devices such as reactors or inductors, e.g. provided with one winding.

The electrical insulation used in the current-carrying winding means of a stationary electromagnetic device according to the invention is intended to be able to

handle very high voltages and the consequent electric and thermal loads which may arise at these voltages. By way of example, power transformers in accordance with the invention may have rated powers from a few hundred kVA up to more than 1000 MVA and with rated voltages ranging from 3-4 kV, preferably from 10 kV, up to very high transmission voltages of 400-800 kV. At high operating voltages, partial discharges, or PD, constitute a serious problem for known insulation systems. If cavities or pores are present in the insulation, internal corona discharge may arise whereby the insulating material is gradually degraded eventually leading to breakdown of the insulation. The electric load on the electrical insulation of the winding means is reduced by ensuring that the inner layer of the insulation is at substantially the same electric potential as the inner conducting means and the outer layer of the insulation is at a controlled, e.g. earth, potential. Thus the electric field in the intermediate layer of insulating material between the inner and outer layers is distributed substantially uniformly over the thickness of the intermediate layer. Furthermore, by having materials with similar thermal properties and with few defects in the layers of the insulating material, the possibility of PD is reduced at a given operating voltages. The winding means can thus be designed to withstand very high operating voltages, typically up to 800 kV or higher.

Although it is preferred that the electrical insulation of each winding should be extruded in position, it is possible to build up an electrical insulation system from tightly wound, overlapping layers of film or sheet-like material. Both the semiconducting layers and the electrically insulating layer can be formed in this manner. An insulation system can be made of an all-synthetic film with inner and outer semiconducting layers or portions made of polymeric thin film of, for example, PP, PET, LDPE or HDPE with embedded conducting particles, such as carbon black or metallic particles and with an insulating layer or portion between the semiconducting layers or portions.

For the lapped concept a sufficiently thin film will have butt gaps smaller than the so-called Paschen minima, thus rendering liquid impregnation unnecessary. A dry, wound multilayer thin film insulation has also good thermal properties.

Another example of an electrical insulation system is similar to a conventional cellulose based cable, where a thin cellulose based or synthetic paper or non-woven material is lap wound around a conductor. In this case the semiconducting layers, on either side of an insulating layer, can be made of cellulose paper or non-woven material made from fibres of insulating material and with conducting particles embedded. The insulating layer can be made from the same base material or another material can be used.

Another example of an insulation system is obtained by combining film and fibrous insulating material, either as a laminate or as co-lapped. An example of this insulation system is the commercially available so-called paper polypropylene laminate, PPLP, but several other combinations of film and fibrous parts are possible. In these systems various impregnations such as mineral oil.

CLAIMS

1. A high voltage stationary electromagnetic device comprising a core of magnetic material having a relative permeability greater than 1 and current-carrying winding means for generating an H-field, characterised in that the core is constructed and arranged so that, in use of the core assembly, current carried by the winding means gives rise to a B-field in the core which substantially follows the said H-field.

2. An electromagnetic device according to claim 1, characterised in that the core is made up of a plurality of wires or cables.

3. An electromagnetic device according to claim 2, characterised by that the wires or cables have an outer insulating layer.

4. An electromagnetic device according to claim 2 or 3, characterised in that the wires or cables consists of oriented material.

5. An electromagnetic device according to claim 2 or 3, characterised in that the wires or cables consists of an amorphous material.

6. A magnetic assembly according to any one of claims 2 to 5, characterised in that the wires or cables are of rectangular or circular cross-section.

7. An electromagnetic device according to any one of claims 2 to 6, characterised in that the wires or cables are provided with means for transferring magnetic flux therebetween.

8. An electromagnetic device according to claim 7, characterised in that the flux transfer means comprises a

composite of soft magnetic powdered material in which the wires or cables are at least partly embedded.

9. An electromagnetic device according to claim 7, characterised in that the flux transfer means comprises a solidified slurry of soft magnetic material in which the wires or cables are at least partly embedded.

10. An electromagnetic device according to claim 1, characterised in that the magnetic core comprises a polymer matrix with a relative permeability greater than 1.

11. An electromagnetic device according to claim 1, characterised in that the core consists of limbs and yokes of laminated sheet material and that at least some of the joints between limbs and yokes include rounded, flux carrying corner pieces.

12. An electromagnetic device according to claim 11, characterised in that the or each flux carrying corner piece at least partly consists of compacted material in the form of a soft magnetic powder material.

13. An electromagnetic device according to claim 11, characterised in that the or each flux carrying corner piece at least partly consists of a compacted material formed from a solidified soft magnetic slurry.

14. An electromagnetic device according to claim 11, characterised in that the or each flux carrying corner piece at least partly consists of laminated sheet material.

15. An electromagnetic device according to claim 1, characterised in that the core comprises limbs and yokes of laminated sheet material and soft magnetic powder material reinforced with magnetic wires or cables.

16. An electromagnetic device according to claim 1, characterised in that the core comprises limbs and yokes of

laminated sheet material and compact material formed of a solidified magnetic slurry reinforced with magnetic wires or cables.

17. An electromagnetic device according to any one of the preceding claims, characterised in that said winding means comprises at least one winding wound from cable comprising inner electrically conducting means and, surrounding the latter, outer solid electrically insulating means.

18. An electromagnetic device according to claim 17, characterised in that said solid electrically insulating means comprises magnetically permeable plastics material within which the electric field, created by current passing along the cable, is confined in use of the magnetic core assembly.

19. An electromagnetic device according to claim 17 or 18, characterised in that the electrically insulating means is of substantially unitary construction comprising an inner layer of semiconducting material in electrical contact with said electrically conducting means, an outer layer of semiconducting material at a controlled electrical potential along its length and an intermediate layer of electrically insulating material between the said inner and outer layers.

20. An electromagnetic device according to claim 19, characterised in that the semiconducting outer layer has a volume resistivity of from 1 to 10^5 ohm·cm.

21. An electromagnetic device according to claim 19, characterised in that the semiconducting outer layer has a volume resistivity of from 10 to 500 ohm·cm, preferably from 10 to 100 ohm·cm.

22. An electromagnetic device according to any one of claims 19 to 21, characterised in that the resistance per

axial unit length of the semiconducting outer layer is from 5 to 50,000 ohm.m^{-1}.

23. An electromagnetic device according to any one of claims 19 to 21, characterised in that the resistance per axial unit of length of the semiconducting outer layer is from 500 to 25,000 ohm.m^{-1}, preferably from 2,500 to 5,000 ohm.m^{-1}.

24. An electromagnetic device according to any one of claims 19 to 23, characterised in that the said outer layer is contacted by conductor means at said controlled electrical potential at spaced apart regions along its length, adjacent contact regions being sufficiently close together that the voltages of mid-points between adjacent contact regions are insufficient for corona discharges to occur within the electrically insulating means.

25. An electromagnetic device according to any one of claims 19 to 23, characterised in that said controlled electrical potential is at or close to ground potential.

26. An electromagnetic device according to any one of claims 19 to 25, characterised in that the said intermediate layer is in close mechanical contact with each of said inner and outer layers.

27. An electromagnetic device according to any one of claims 19 to 25, characterised in that the said intermediate layer is joined to each of said inner and outer layers.

28. An electromagnetic device according to claim 27, characterised in that the strength of the adhesion between the said intermediate layer and the semiconducting outer layer is of the same order of magnitude as the intrinsic strength of the material of the intermediate layer.

29. An electromagnetic device according to claim 27 or 28, characterised in that the said layers are joined together by extrusion.

30. An electromagnetic device according to claim 29, characterised in that the inner and outer layers of semiconducting material and the insulating intermediate layer are applied together over the conducting means through a multi layer extrusion die.

31. An electromagnetic device according to any one of claims 19 to 30, characterised in that said inner layer comprises a first plastics material having first electrically conductive particles dispersed therein, said outer layer comprises a second plastics material having second electrically conductive particles dispersed therein, and said intermediate layer comprises a third plastics material.

32. An electromagnetic device according to claim 31, characterised in that each of said first, second and third plastics materials comprises an ethylene butyl acrylate copolymer rubber, an ethylene-propylene-diene monomer rubber (EPDM), an ethylene-propylene copolymer rubber (EPR), LDPE, HDPE, PP, PB, PMP, XLPE, EPR or silicone rubber.

33. An electromagnetic device according to claim 31 or 32, characterised in that said first, second and third plastics materials have at least substantially the same coefficients of thermal expansion.

34. An electromagnetic device according to claim 31, 32 or 33, characterised in that said first, second and third plastics materials are the same material.

35. A transformer having a magnetic core assembly as claimed in any one of the preceding claims.

36. A reactor having a magnetic core assembly as claimed in any one of claims 1 to 34.

37. A method of modifying a magnetic core comprising limbs and yokes connected to define at least one angled joint, characterised in that the method comprises fitting at least one corner piece having a curved contour in the, or at least some of the, angled joint(s).

38. A magnetic core assembly for a stationary electromagnetic device, comprising a core of magnetic material having a relative permeability greater than 1 and current-carrying winding means for generating an H-field, characterised in that the core is constructed and arranged so that, in use of the core assembly, current carried by the winding means gives rise to a B-field in the core which substantially follows the said H-field.

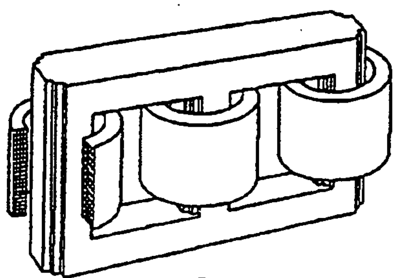

Fig. 1

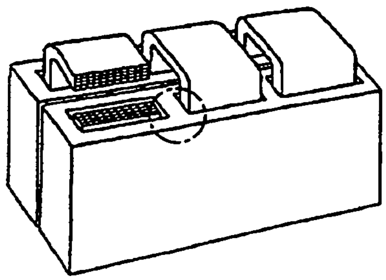

Fig. 2

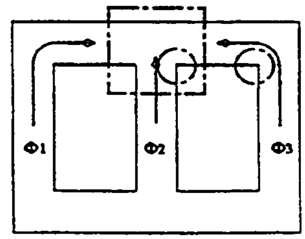

Fig. 3

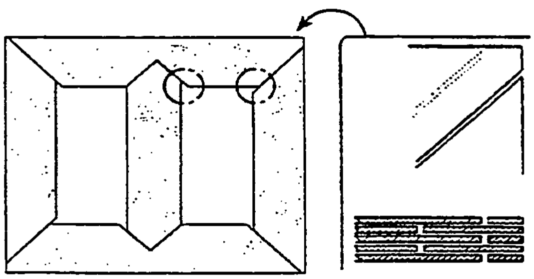

Fig. 4

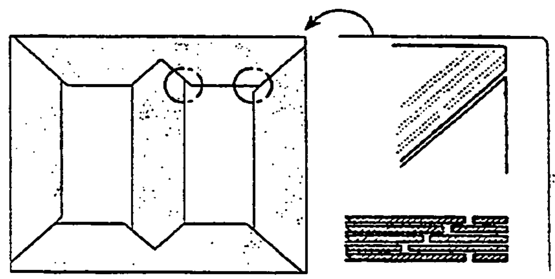

Fig. 5

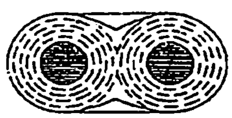

Fig. 6

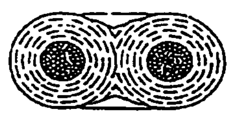

Fig. 7

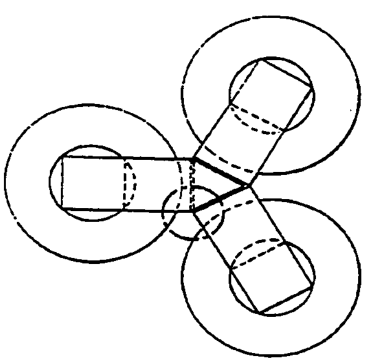

Fig. 8

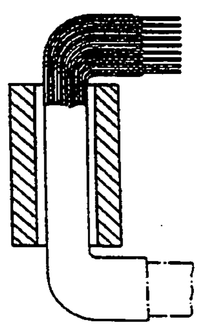

Fig. 9

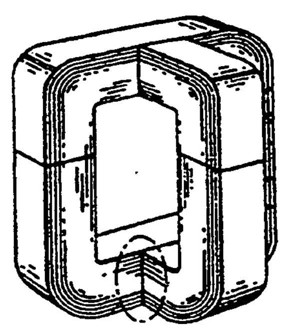

Fig. 10

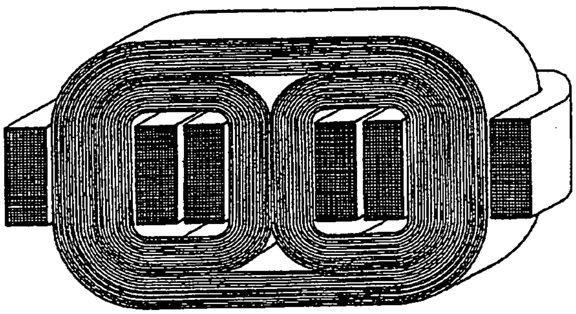

Fig. 11

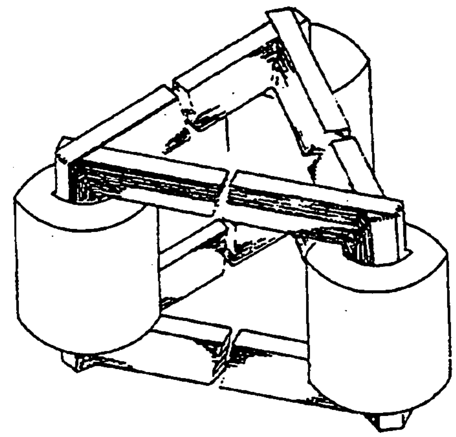

Fig. 12

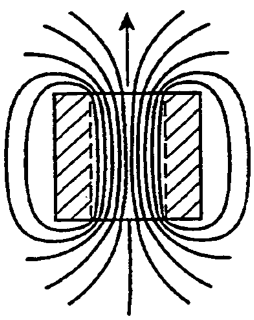

Fig. 13

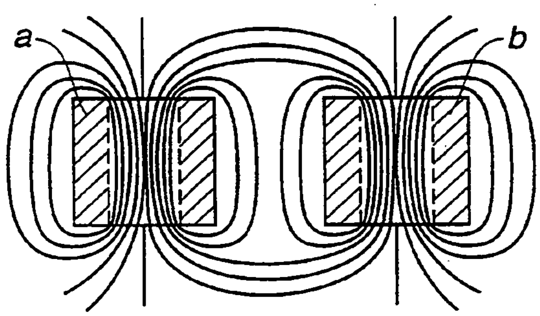

Fig. 14

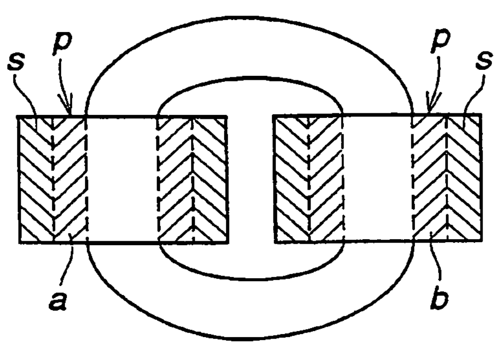

Fig. 15

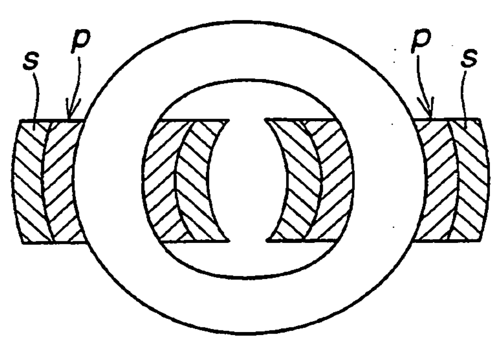

Fig. 16

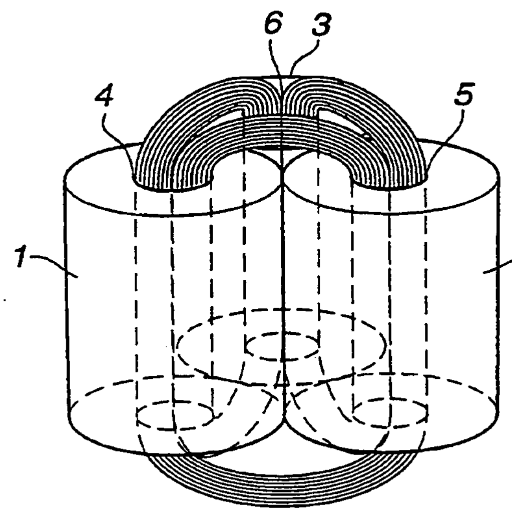

Fig. 17a

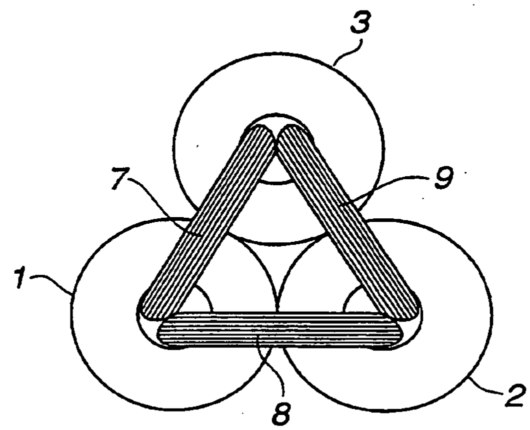

Fig. 17b

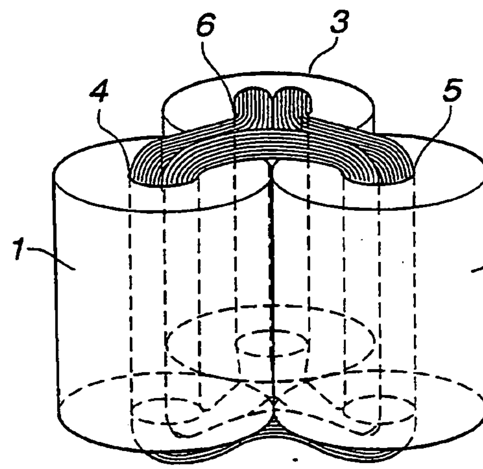

Fig. 18a

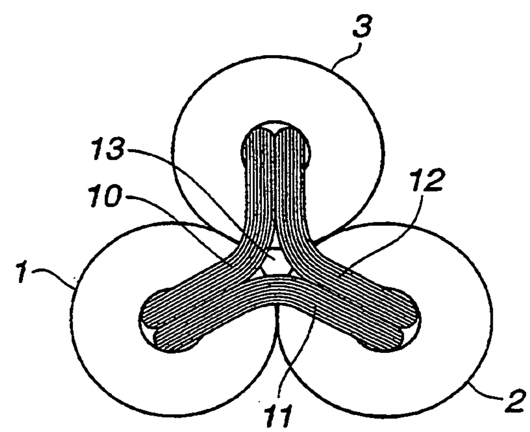

Fig. 18b

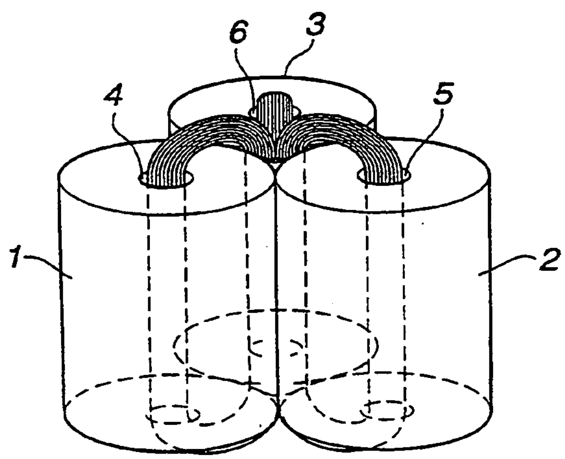

Fig. 19a

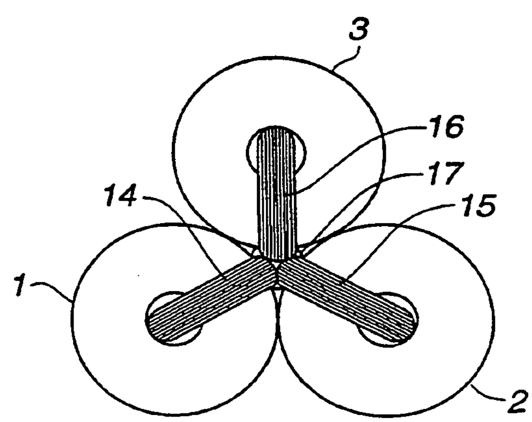

Fig. 19b

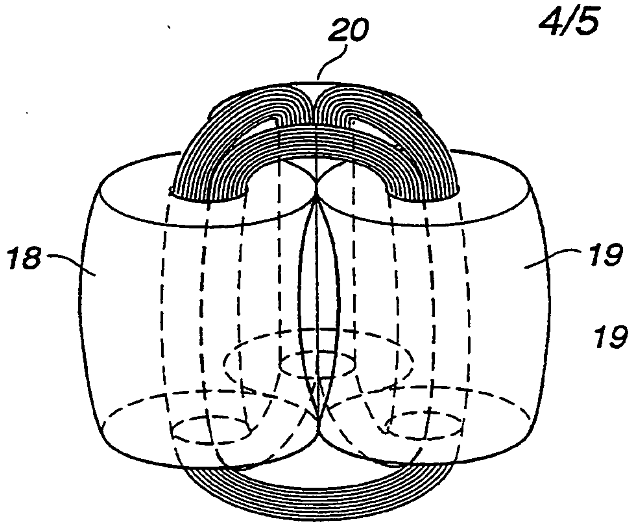

Fig. 20a

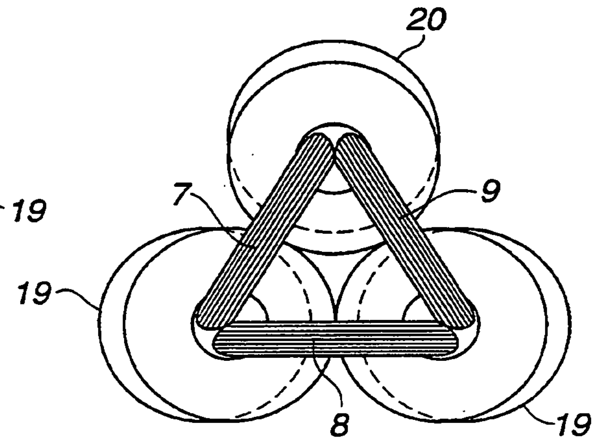

Fig. 20b

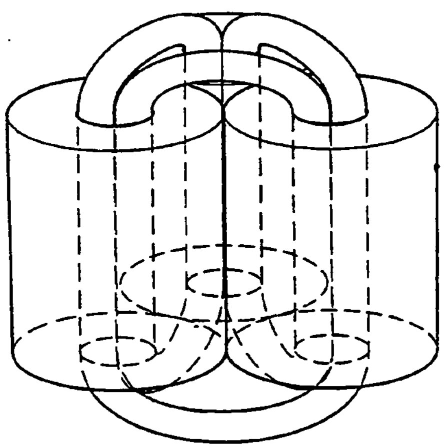

Fig. 21

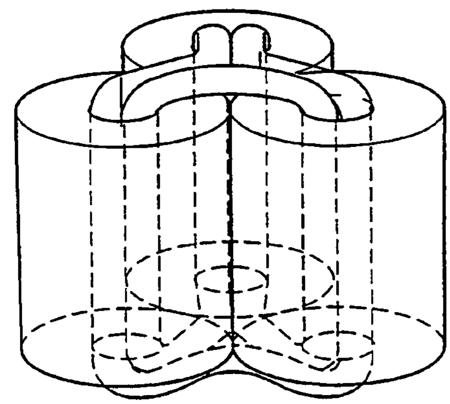

Fig. 22

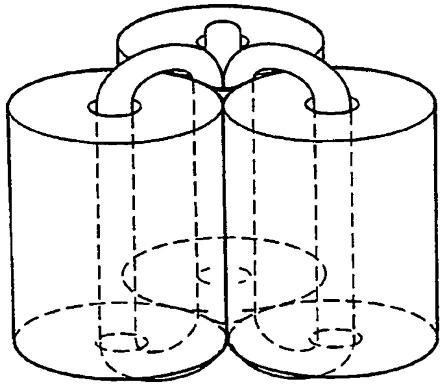

Fig. 23

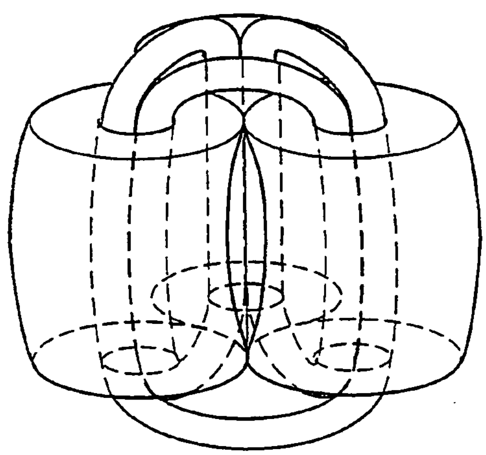

Fig. 24

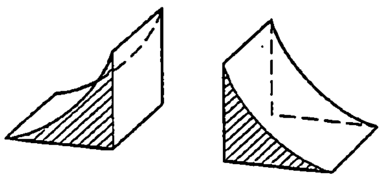

Fig. 25

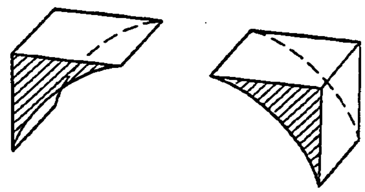

Fig. 26

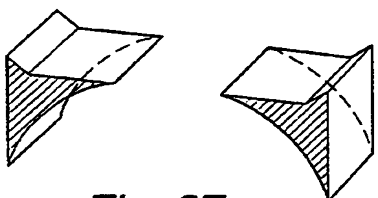

Fig. 27

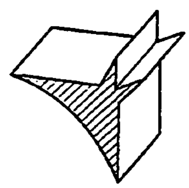

Fig. 28

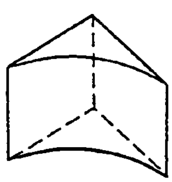

Fig. 29

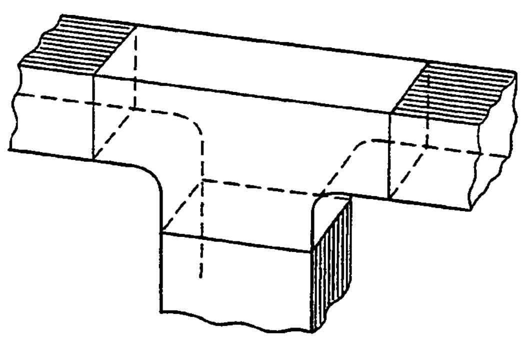

Fig. 30

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 98/07743

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01F3/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 91 09442 A (BENFORD SUSAN M) 27 June 1991 see page 16, line 1 - page 19, last line	1-3,6, 35,36,38
X	US 3 304 599 A (TELETYPE CORPORATION) 21 February 1967 see column 2, line 25 - line 52	1-3,38
A	DE 37 26 346 A (VACUUMSCHMELZE GMBH) 16 February 1989 see column 1, line 60 - column 2, line 3	5
A	GB 2 046 142 A (AEROSPATIALE) 12 November 1980 see page 2, line 87 - line 111	10
A	DE 846 583 C (SIEMENS) 14 August 1952 see page 2, line 36 - line 86	11
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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

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Date of the actual completion of the international search	Date of mailing of the international search report
29 March 1999	08/04/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Vanhulle, R

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 98/07743

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WO 91 15862 A (ZYLBERSZAC MOJZESZ) 17 October 1991	
A	US 2 962 679 A (GENERAL ELECTRIC) 29 November 1960	
A	FR 841 351 A (BRAMI) 17 May 1939	

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Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 98/07743

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